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DRYING OF REFRACTORY LINER BOARDS

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Laboratory tests have been done to assess the feasibility of using microwaves to manufacture refractory liner boards. Results show that microwaves cured and dried the product about ten times faster than the conventional gas-oven process. The quality of boards dried with microwaves appears to be as good or better than of those dried with gas. The potential for fast, energy-optimized drying in a small space has been demonstrated. Economically, the energy-cost of using microwaves is comparable to using gas when drying the last 30% moisture content, that is, for about the last 50% of the present gas-drying time. For higher moisture contents, such as encountered in the early stages of drying, the energy can be supplied at a lower cost by gas.

INTRODUCTION

An Ontario company is now producing 91,000 kg/week of refractory liner boards for use by the steel industry. These boards are used along the inside of molds to control cooling and shrinkage of the steel when casting. The refractory board industry is presently very competitive, and the customer is highly motivated to improve his operation. He is interested in the possibility of using microwaves, or some other electrotechnology, to gain a competitive advantage.

Liner boards are formed from wet slurries of magnesium oxide, silica, or kyanite with a phenolic binder. The slurries are molded on a vacuum table which removes as much water as possible leaving a soft, uncured product. The boards are now cured in a gas-oven and dried to less than one percent final moisture content. This dryness is necessary to avoid steam explosions when the molten steel comes into contact with the liner boards.

On 21 October 1987, B. Miettinen (Central Region) and T. Cave, toured the plant, and met with the customer to discuss the opportunities. It was decided to evaluate the possibility of adding a microwave or radio frequency section to the end of the existing gas-oven. Generally, it was thought that this would offer the following advantages:

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1 Since microwaves usually work more quickly than convection heating, and since power supplies may be located separately from the applicators, floor space requirements may be much lower than for gas-ovens.

2 Product quality may be enhanced since using microwaves to dry the center of the product should reduce or eliminate the need to overheat the outside surface of the boards. This could reduce scorching and the formation of skins or crusts.

3 It may be possible to individually optimize energy use on a board-by-board basis with the aid of temperature monitoring. This potential cost-reduction technique will be discussed later.

4 Microwaves could be used in the form of an addition at the end of the existing gas-oven. This type of modification presents a fairly low-risk option.

5 Using a volumetric heating method near the end of the gas-drying process could take advantage of the relative costs and efficiencies of the two drying technologies to keep overall unit costs to a minimum. Microwave drying is energy-efficient at low moisture contents because the microwaves can pass directly through dry outside layers which impede convection heating.

Accordingly, it was decided to proceed to laboratory testing to quantitatively establish costs and benefits.

RESULTS

Technically, microwaves dry and cure liner boards extremely quickly doing in a few minutes what conventionally takes about 2 hours. The quality of boards dried with microwaves appears to be as good as, if not better than those dried with gas. The potential for fast, energy-optimized drying in a small space has been demonstrated.

Economically, the energy-cost of using microwaves is comparable to using gas when drying the last 30% moisture content (ie. for about the last 50% of the present gas-drying time). For higher moisture contents, such as encountered in the early stages of drying, the energy can be supplied at a lower cost by gas.

Energy and equipment costs are summarized for a variety of operating conditions in Graphs 7 and 8. Existing production levels could be increased up to 100% using microwaves for an energy-cost comparable to that of gas. For larger increases, gas can supply part of the required energy more cheaply.

TESTING AND ANALYSIS

About twenty samples of the refractory liner boards were obtained from the manufacturer. They were 25 X 25 cm, weighed about a kilogram each, and had moisture contents between 90% and 110% of the dry mass. Testing consisted of monitoring sample masses as they were dried by microwaves and radio frequencies at various power levels, and, for comparison, by a convection oven operating at 200 C. Mass data were divided by a final sample mass obtained after overnight drying to obtain a dry basis moisture content. All moisture contents in this report are quoted as a percent of the dry mass.

Graph 1 shows the drying characteristics of a typical sample when placed in the convection oven. At 200 C it takes about 2.5 h to dry. The crucial point to note is that the last 10% of the drying takes about 30% of the total time. Convection drying becomes progressively less efficient as the product becomes drier. This drying curve models the actual behavior in the customer's gas-oven and will be used in comparative calculations. However, it is different in one important respect. The customer operates the first few metres of his oven at between 230-280 C, (depending on the product), to bring the temperature up very quickly. This enables his total drying time to be reduced to just two hours.

Graph 1 also shows the results of microwave heating using a moderate power of 4.3 kW. Total drying time is about 10 min. Microwaves clearly have the ability to dry this product very quickly even at low moisture contents. No degradation of the structure of the boards was observed even at the highest drying rates. It was possible to produce localized surface discoloration if care was not taken to assure uniform heating.

Radio frequency testing was done in a 6 kW through-field applicator. Heating was slow, taking about 60 min to reach 100 C. Arcing was a problem and samples were damaged by the discharges. Radio-frequency drying was judged to be unsuitable for this process.

Graph 2 illustrates how the temperature of the product changes as the microwaves are applied. Note that it holds steady at 100 C, the boiling point of water, then quickly rises just as the last of the water is removed. This is because microwaves are absorbed by water better than they are absorbed by the refractory. Therefore, any water present will be heated, turned to steam at 100 C, and forced out of the board by the steam pressure. This will continue until all of the water has been removed, only then will the microwaves start coupling to the refractory and heat it up beyond 100 C. This property may be very useful for process control. In principle, the product temperature could be monitored on a board-by-board basis (possibly with a non-contact optical method) to watch for the temperature suddenly rising past 100 C. At that point, the dry board could be ejected from the oven without wasting any energy on excess heating.

Tests were run on many samples while the applied microwave power was systematically varied. Some of these results are displayed in Graph 3. Here the application of microwaves is expressed in terms of the amount of energy applied per kilogram of refractory. This takes into account the variation in applied power and sample size. But as can be seen from the graph, there remains a significant level of variability in the

initial moisture contents, and in the normalized drying rates. This is probably due to variations in the production process, ie. viscosity of the slurry, length of time on the vacuum table, etc.

Graph 4 is an expanded view of Graph 3. It zooms-in on the region of most interest, drying the last 10%. The graph also shows a smooth curve which is a least-squares fit to the data. The fitted curve is used as a condensed expression of the results of all the microwave drying tests. The point of this graph is to highlight the variability in the findings. A smooth fit is a good way to use the results in further calculations. However, it must be kept in mind that individual boards do not necessarily behave like the average, and because of this, any estimates have an uncertainty associated with them. Cost estimates probably have an overall uncertainty of at least 10%.

To take the test results and develop cost estimates, some assumptions will be made.

> Assumption 1. The refractory is 'completely dry' when its moisture content is less than one half of 1%.
>
> Assumption 2. The use of microwaves will be in the form of an add-on section at the end of the gas-oven.
>
> Assumption 3. As production is increased, the existing gas-oven can be used without any additional cost.

Consider then, if the line-speed is increased so that the boards spend only 80% as much time in the oven as they did previously, production will be increased by 25%. To express this inverse relationship in terms of realistic production figures make:

> Assumption 4. The plant presently produces 91,000 kg/week of dry refractory board (or, 200,000 lb/week) by working a 24 h day, 5 days a week.

With these assumptions, Graph 5 indicates how production volumes will vary from the present 758 kg/h as a function of time spent in the gas-oven. For example, the 80% gas-drying fraction noted above, would mean 940 kg/h of production.

To determine how the microwave requirements change as the production line speed is increased, consult Graph 1 to see how damp the boards would be as they emerge from the gas-oven. In the example, an 80% gas-drying fraction would leave a moisture content of 5.6%. Now look at Graph 4 to determine the specific energy required to remove this moisture. A 5.6% moisture content would require an extra 0.067 kWh/kg to be dry at 0.75 kWh/kg. Now multiply by the new production rates to obtain the necessary microwave power. From the example of the last paragraph, an 80% gas-drying time results in 940 kg/h. This, times the net 0.067 kWh/kg specific energy, means the required microwave power is 63 kW. Graph 6 indicates what the required microwave power would be at other gas-drying fractions.

Capital equipment costs are estimated based on the following rule-of-thumb:

Assumption 5. Suitable microwave equipment can be purchased at a cost of about $5,000 Canadian per kilowatt of microwave power.

This is probably a slight over-estimate, but note that this does not include the cost of an electrical service upgrade if necessary. Graph 7 displays the equipment price estimates which follow from this assumption.

Energy costs are calculated based on an electricity price of 4 cents/kWh. The efficiency of converting this electricity into microwaves depends on the equipment. Generally, microwave systems operating at 2.45 GHz are about 50% efficient, and equipment operating at 915 MHz converts about 80%. The 50% efficiency equipment is the most common type, so it will be assumed in the following calculations that;

Assumption 6. The cost of microwave energy will be 8 cents/microwave kWh.

Graph 8 shows how these considerations apply as a function of the gas-drying fraction.

Another cost which can be important is maintenance for the microwave system. The largest factor is the price of replacement magnetrons. Magnetrons are the electron tubes which actually generate the microwaves. They last between 2,000 and 10,000 hours depending on the quality of the equipment and the manner of usage. Generally, the fewer times that they are turned-on and off, the longer they will work. In this application operation would be virtually continuous, so lifetimes of 6,000 hours or more should be obtained. The price of replacement magnetrons depends strongly on the type of equipment purchased. However, to give a rough idea, an industry standard 6 kW magnetron now costs $4,300 Canadian. This cost factor should be compared to the maintenance expenses of the customer's present gas-system.

HOW TO USE THESE FINDINGS

The foregoing data, assumptions, and calculations have been presented in full so that they can be used under a wide variety of projected situations. However, for the immediate purpose of evaluating an add-on microwave oven, the focus will be on comparing costs with gas-drying.

For gas-powered extensions, the added cost per unit of additional product will be approximately constant regardless of the size of the addition. To see this, consider extending the oven by 10%. This would obtain 10% more production. But since there is no change in the process drying efficiency, it would be necessary to purchase about 10% more gas. So the overall unit drying cost would remain the same as before.

To determine what the actual gas-drying cost is, it would be necessary to meter the gas consumed by the oven. This is not done, but some estimates can be made. The customer's total gas bill is between eleven and twelve thousand dollars per month. It is thought that about 80% of this is spent on the oven in question. Since present production is 91,000 kg/week, an average gas-drying unit-cost of about 2.5 cents/kg is implied.

With this estimate, the hourly energy costs of gas-powered extensions have been calculated and are shown in Graph 8. The graph compares the costs of gas and microwave add-on ovens for different entry moisture contents. It is assumed that production is being increased by raising the line-speed through the existing gas-oven. Although there is about a 10% uncertainty in both the gas and the microwave cost projections, it is clear that the two are about the same for drying the last 30% moisture content. When more moisture needs to be removed, the gas-oven becomes progressively more energy-cost effective. From Graph 1, it can be seen that for the add-on oven to have an entry moisture content of 30%, the liner boards would only have to spend 50% of the present drying time in the existing gas-oven. This implies that production could be doubled with a microwave oven for the same energy-cost as a gas-powered extension. If larger production increases are needed, then gas can provide a part of the energy at a lower cost.

RECOMMENDATIONS

These findings should be reviewed in detail with the customer. With them, it should be possible to relate the cost of any investment with the expected return in terms of increased production. The customer, if interested, should now be able to propose precise new operating conditions. That is, given the amount of available capital and some production targets, he should be able to specify what moisture contents, power levels and treatment times for which the microwave unit is supposed to work.

At that point, there should probably be a set of full-scale tests done under conditions as close as possible to the final projections. Such focused testing should:

1. Improve the cost projections. Doing detailed testing over a smaller range of parameters would reduce uncertainty.

2. Consider the effects of any metal fillings or reinforcements. These may reduce or improve the effectiveness of the microwaves, but in any case would probably require careful design of the microwave cavity.

3. Address variations in the drying cycle. Final testing could take into account differences in the initial gas-oven temperatures which are used for different products.

Any questions or further requests may be directed to Tom Cave.

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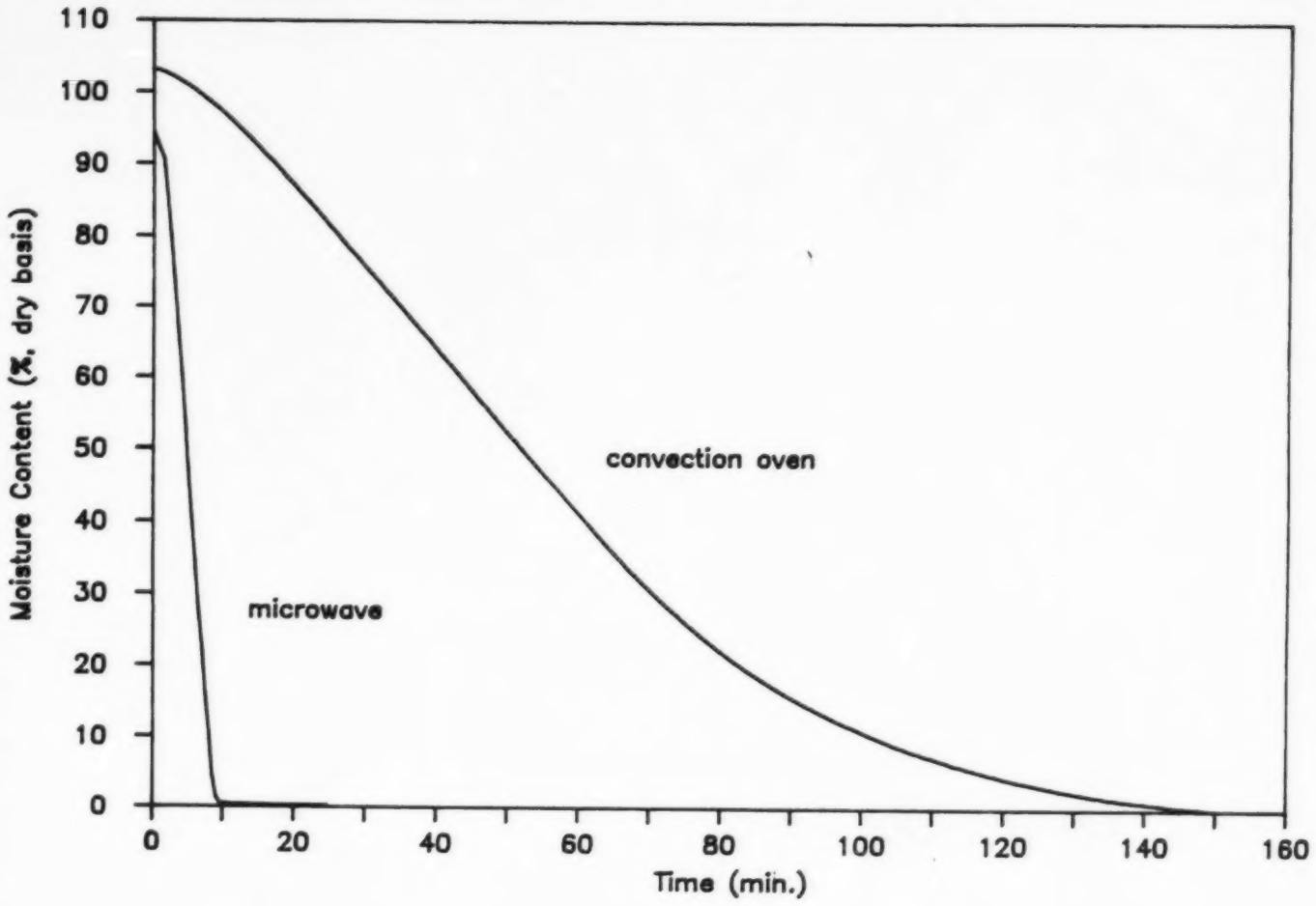
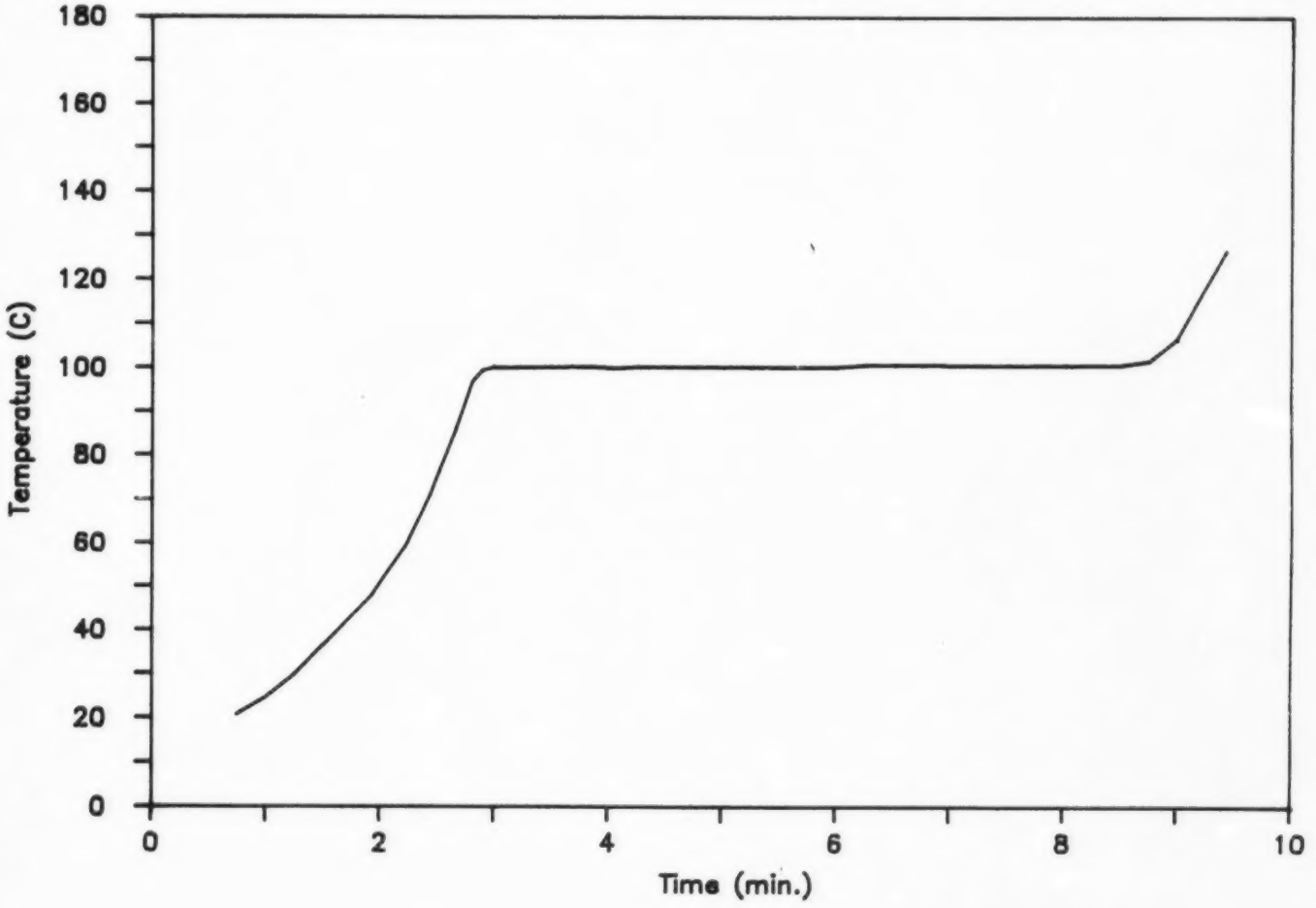
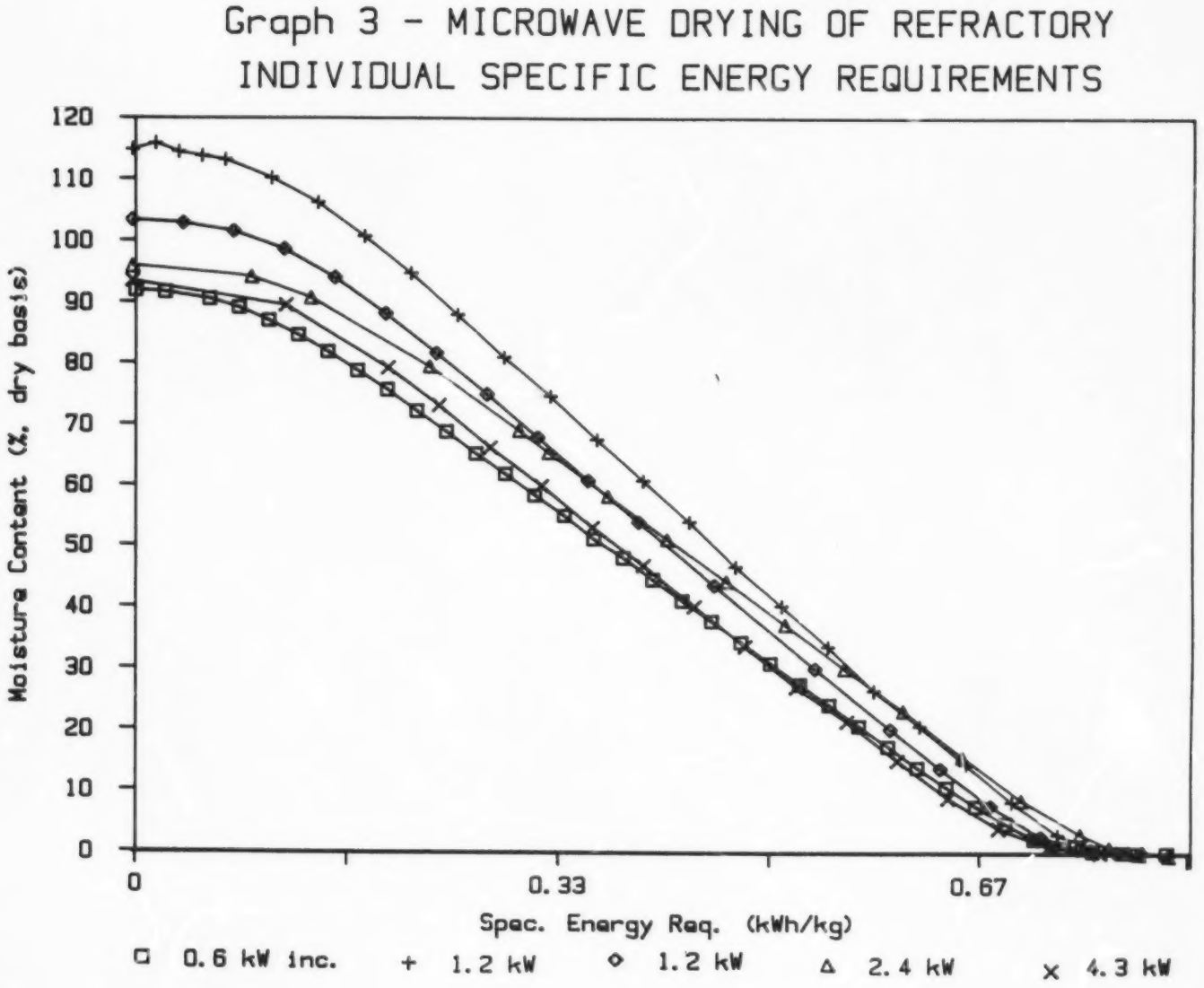
TBC:djb

Graph 1 – DRYING OF REFRACTORY

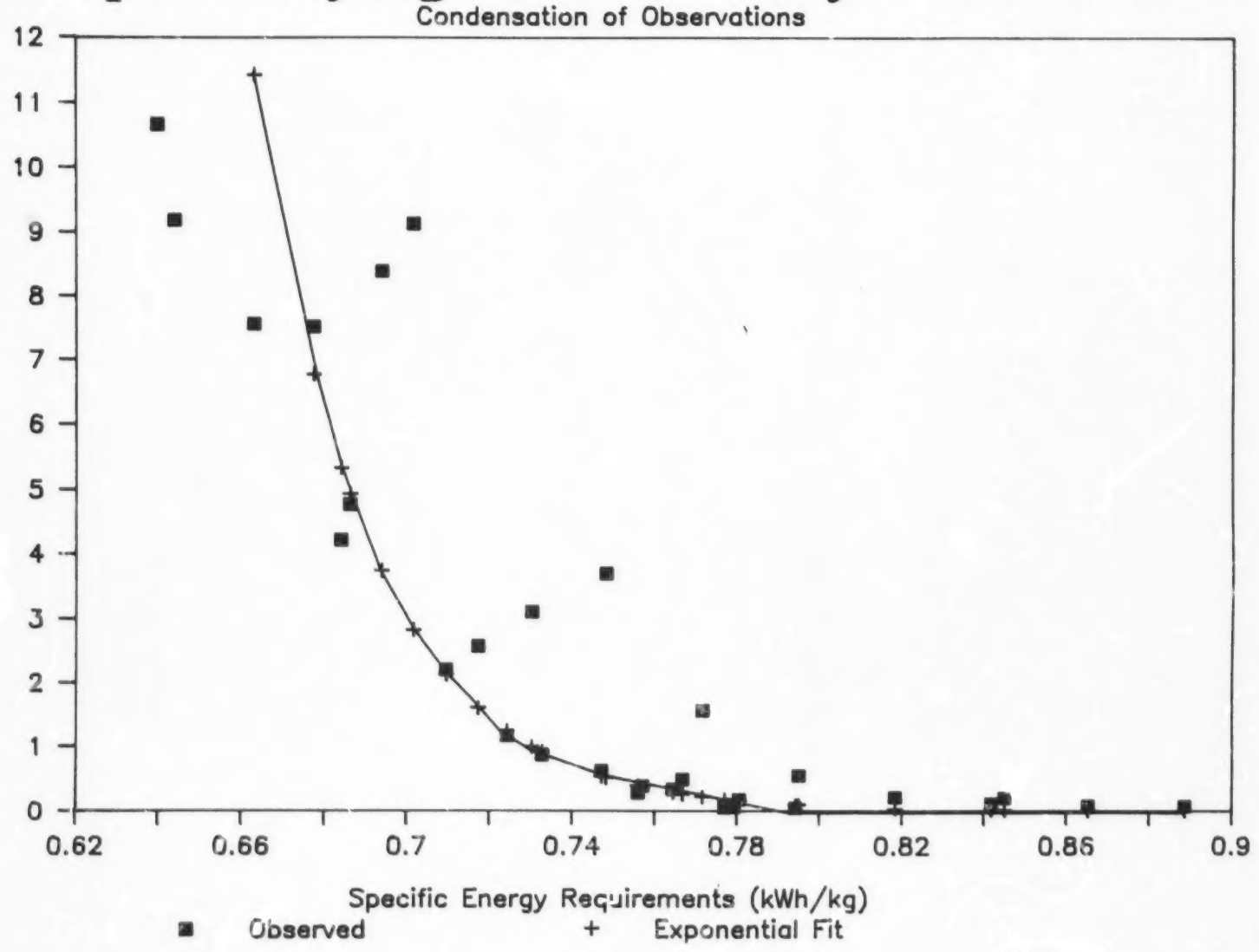


Graph 2 – MICROWAVE DRYING OF REFRACTORY
TEMPERATURE PROFILE (test 5, 4.3 kW incident)

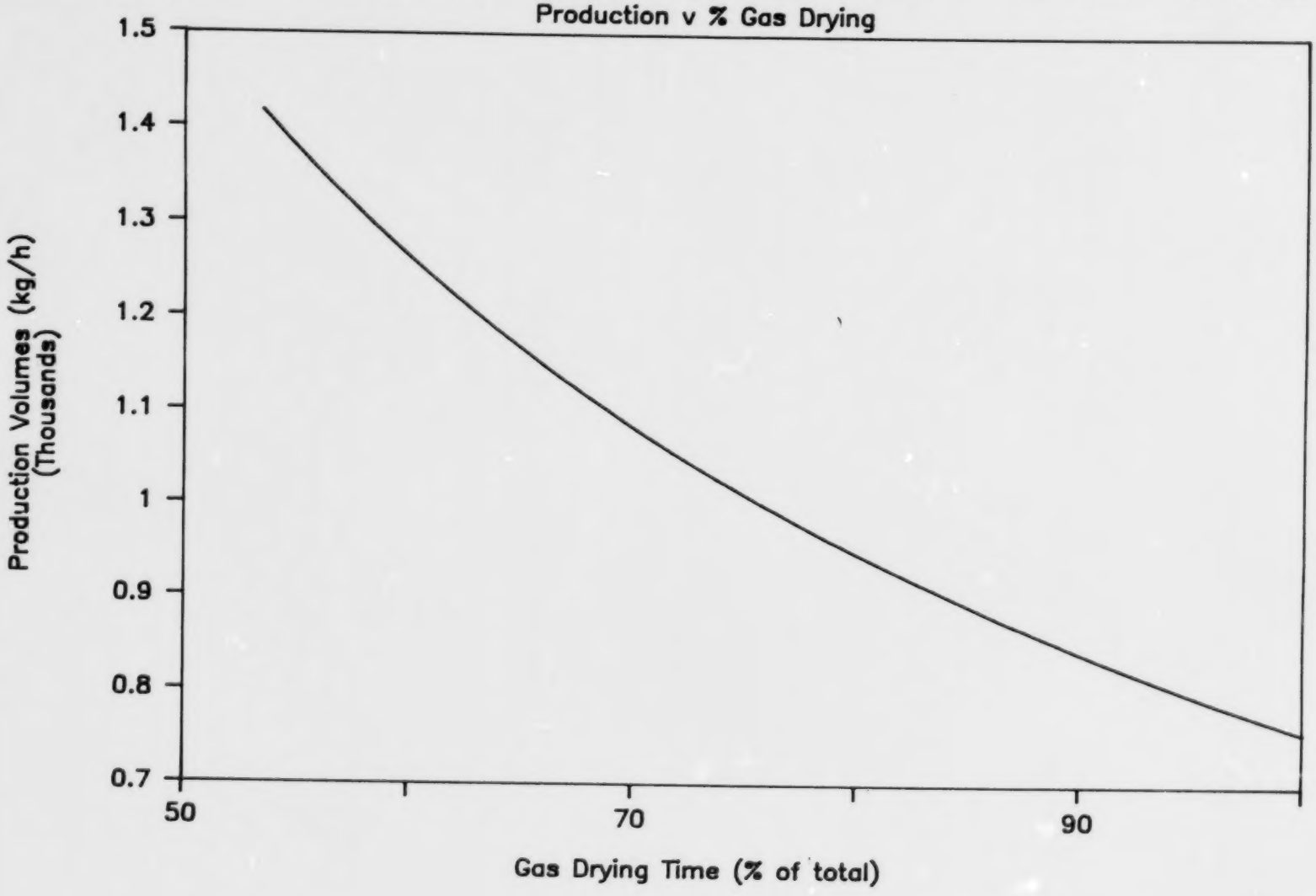



Graph 3 - MICROWAVE DRYING OF REFRACTORY
INDIVIDUAL SPECIFIC ENERGY REQUIREMENTS
Moisture Content (%, dry basis)
120
110
100
90
80
70
60
50
40
30
20
10
0
0
0.33
0.67
Spec. Energy Req. (kWh/kg)
□ 0.6 kW inc.
+ 1.2 kW
◇ 1.2 kW
△ 2.4 kW
× 4.3 kW

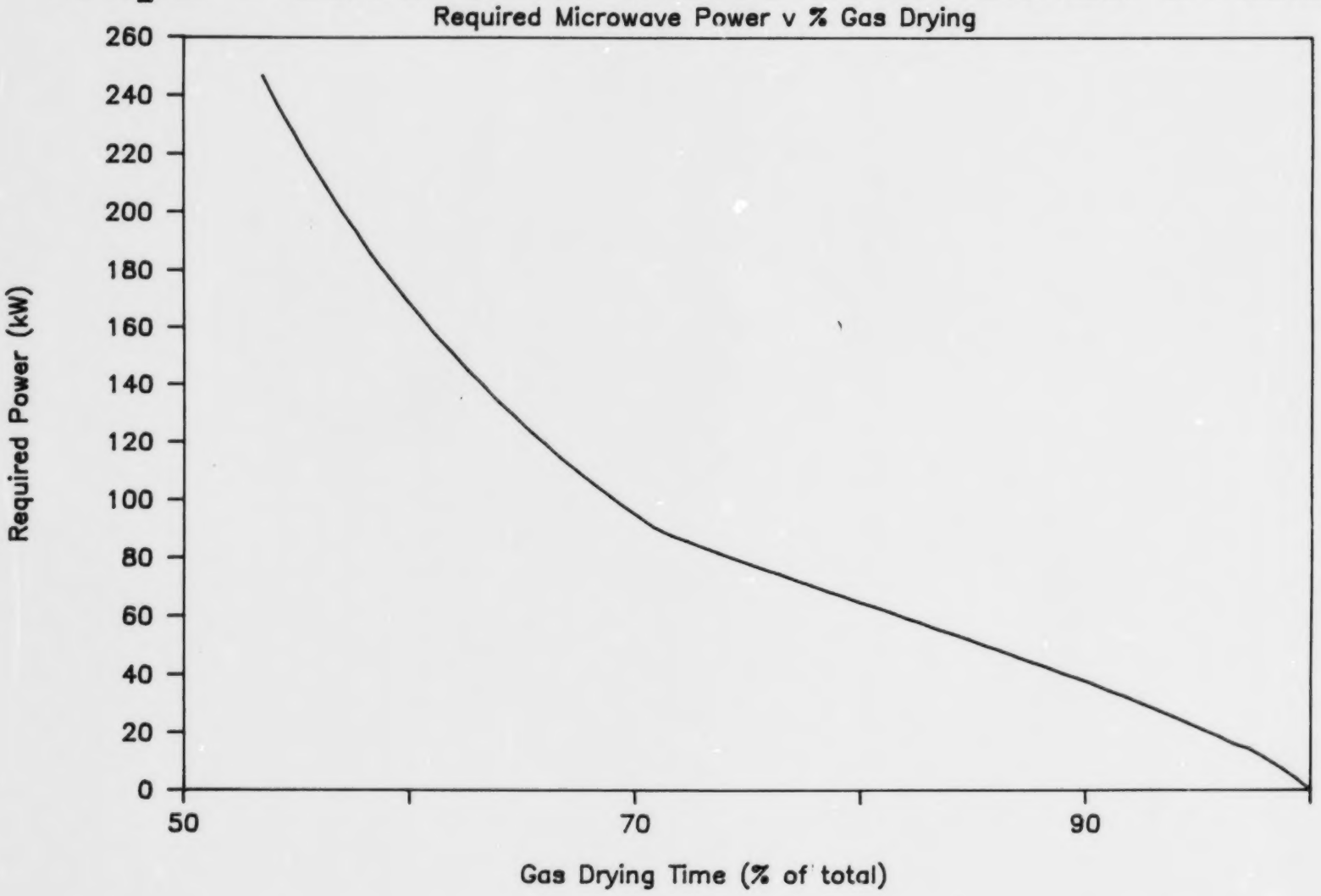
Graph 4 Drying of Refractory Liner Boards



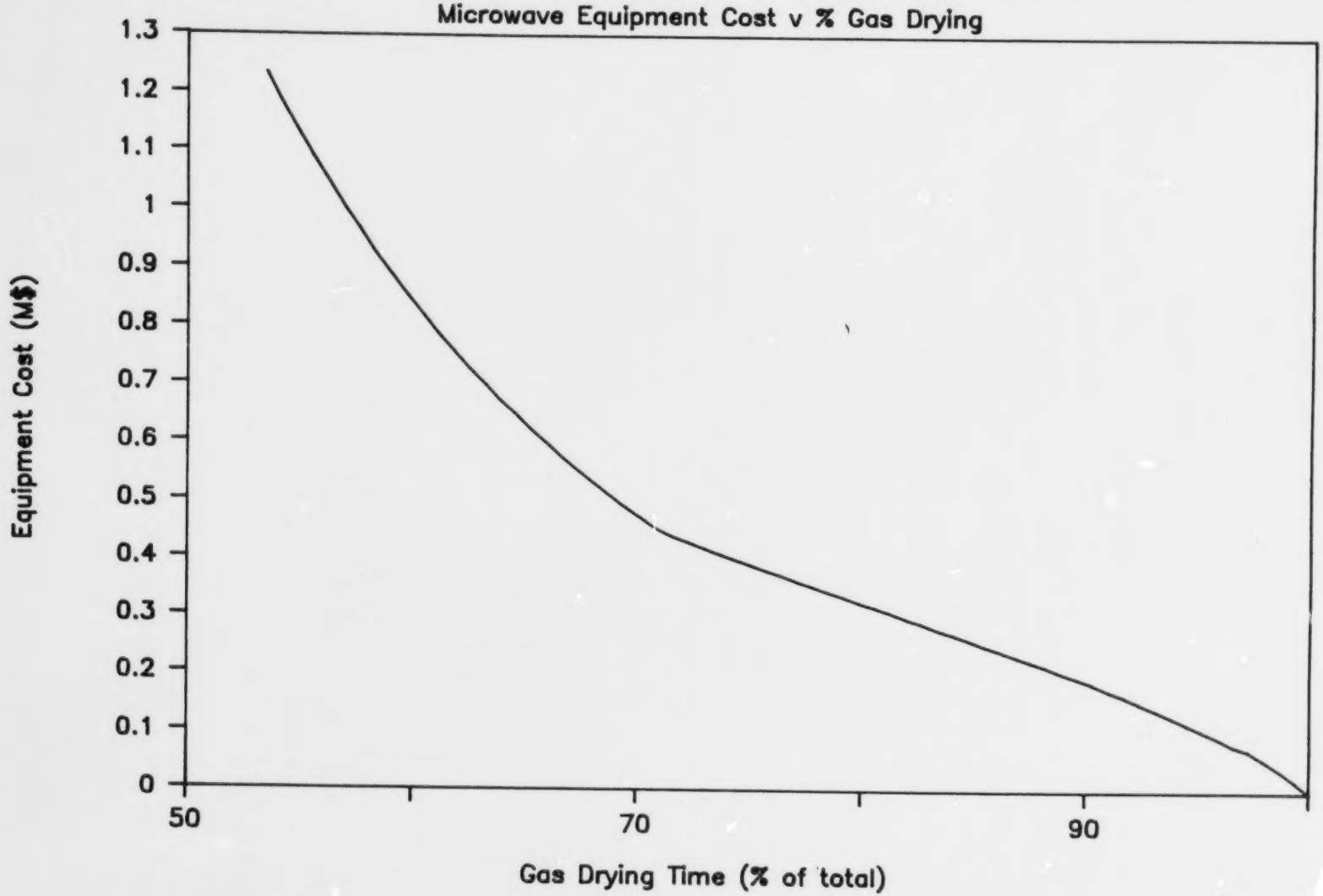
Graph 5 DRYING OF REFRACTORY LINER BOARDS



Graph 6 DRYING OF REFRACTORY LINER BOARDS



Graph 7 DRYING OF REFRACTORY LINER BOARDS



Graph 8 Drying of Refractory Boards

Comparative Energy Costs of Oven Extensions